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FERTILIZATION STUDIES IN A PRECAMBRIAN SHIELD LAKE: KUSHOG LAKE, HALIBURTON COUNTY

February, 1974

Research Report W51

Ontario
Ministry of the Environment

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FERTILIZATION STUDIES IN A PRECAMBRIAN SHIELD LAKE: KUSHOG LAKE, HALIBURTON COUNTY

by

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Research Branch

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ABSTRACT

Kushog Lake is an oligotrophic, low alkalinity environ capable of thermal stratification. Late summer trophogenic zone phytoplankton development appears restricted due to a low availability of nitrogen and phosphorus.

Phytoplankton responses associated with in situ isolated epilimnetic water in bags and column enclosures to single and daily feedings of glucose, nitrogen, phosphorus were quite variable. The key nutrient factor influencing phytoplankton development is phosphorus availability. Synergistic responses to C + N + P compared to N + P appears related to an enhanced availability of carbon dioxide.

Differences between algal responses of bag and column enclosures receiving equivalent treatments is attributed to faunal predation.

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INTRODUCTION

Kushog Lake was first examined in 1967 during an investigation of relationships between nutrient availability and phytoplankton developments in several surface waters of Southern Ontario which represented a variety of trophic situations and ranged in alkalinity (as $CaCO_3$) from about 6 - 120 mg/l (Christie, 1968; 1969; 1973a).

Tentative conclusions from the above studies were examined more critically by means of in situ controlled fertilization experiments in a mesotrophic marl lake, Lake-on-the-Mountain (Christie, 1974). Particular emphasis was directed toward the roles of nitrogen and phosphorus, the two nutrients considered the key factors in eutrophication (Fruh, 1966; Vollenweider, 1970).

Kushog Lake, an oligotrophic low alkalinity environ, was chosen as the location for similar investigations in a situation representing the lower end of the alkalinity range.

Before, during, and since the inception of the Kushog study a considerable amount of research has been undertaken to investigate the nutritive factors influencing phytoplankton development in soft water or Shield lakes (Smith, 1969; Johnson et al, 1970; Kerr et al, 1970; Schindler et al, 1971; Schindler,1971, 1973; Schindler at al, 1973; Michalski et al, 1973). To a large extent these approaches have focused on algal responses resulting from additions of inorganic carbon, nitrogen, and phosphorus with less emphasis being directed toward the potential impact of organic carbon enrichment such as may be associated with sewage treatment plant effluents (BOD).

Inasmuch as earlier laboratory studies with Kushog Lake water yielded positive algal responses following enrichment with inorganic and/or organic carbon, in situ fertilization experiments at Kushog were directed toward investigation of the potential impact of organic carbon loading, with or without nitrogen plus phosphorus, as manifested by algal responses. The results of these experiments which were carried out in 1972, and a description of lake limnology as observed in 1971 and 1972 are provided in the following report.

STUDY AREA

Kushog Lake is situated on the Precambrian Shield in Stanhope Township, Haliburton County at a longitude of 78^{o} 04', latitude of 78^{o} 47', and an altitude of 335m above sea level, and forms a part of the Trent River Drainage Basin (Figure 1). The lake, known at one time as Kakwakshebemagog (Ojibway meaning long and narrow), has a surface area of 590 hectares, a volume of 54×10^{6} cubic metres and a shoreline perimeter of 42 kilometers. The maximum depth is about 36 metres with a mean depth of slightly in excess of 9 metres. The bottom consists of four distinct basins, the lower complex of bays being quite shallow. The water level, which is controlled by a dam at the outfall, may vary as much as two metres between spring and autumn, though no variation was evident during the enclosure experiments in 1972. Many cottages, several resorts and a camp for boys are located around the lake.

Characterization of the lake was based on samples obtained at a single mid-lake station, the depth being about

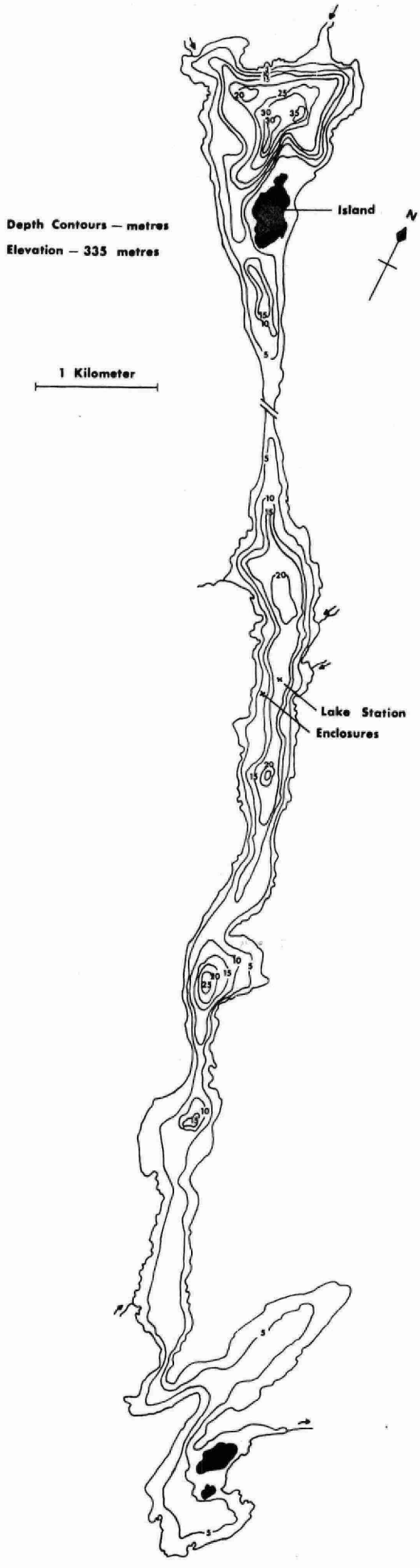

Figure 1

Map of Kushog Lake showing depth contours at 5 metre intervals and the location of the lake sampling station and the enrichment experiments.

16 metres. The enclosure studies were carried out about 25 metres off-shore in water depths which increased from three to in excess of four metres.

MATERIAL AND METHODS

Sampling

Samples from the lake in 1971, 1972 were obtained using a four litre opaque Van Dorn bottle at depths of zero, 3,6,9,12, and 15 metres, monthly in 1971 and bi-weekly in 1972 beginning in May through September.

Analyses

Dissolved oxygen and temperature were determined using a YSI combined probe at one metre intervals to a depth of 15 metres. Water transparency was measured using a secchi disc and the depth of the 1% isophot in 1972 by means of a GM submarine photometer. Various ionic and non-ionic chemical analyses were carried out on unfiltered water samples. Filtered water for other chemical determinations was prepared by passing a 500 ml aliquot of raw water through a glass fibre filter which had been pre-rinsed with two 25 ml washings of the sample to be filtered. Chlorophyll a estimates were based on the residue from a one litre sample treated with 1 ml of saturated $MgCO_3$ and then filtered through a 47 mm 1.2 micron membrane. The above analyses were carried out at the Toronto laboratory of the Ministry of the Environment according to methods described by Brydges (1970). Filtering, pH, carbon dioxide and alkalinity titrations, the latter with a 200 ml aliquot

of raw water following the procedure outlined in Standard Methods (1965), were done on location.

Plankton

Phytoplankton standing crops were sampled at the same time and depth as the above and a one litre sample preserved with Lugol's solution. Concentration, ennumeration and identification procedures have been detailed elsewhere (Christie, 1973a). Phytoplankton productivity measurements were initiated in May each year and done at monthly intervals using the ^{14}C method of Johnson et al (1970) with two light and one dark bottle at six depths. Four hour exposure periods began two hours before midday. Sample radioactivity was determined using a Tricarb scintillation spectrometer and the counts were quench corrected. These data are based only on the radioactivity contained within the seston.

Laboratory Experiment

A laboratory enrichment experiment was carried out in an environmental chamber using 300 ml aliquots of raw water contained in 500 ml sterile screw capped flasks that were agitated on a slowly moving shaker table. Light intensity from a mixture of fluorescent and incadescent lamps was 4000 lux at table level and the temperature was maintained at $20^{o} \pm 2^{o}C$. The cultures were exposed to a 14:10 hour light/dark cycle. Nitrogen and phosphorus, as KNO_3 and KH_2PO_4, were dissolved in distilled water before being added to the cultures.

Field Fertilization Experiments

Fertilization experiments in the lake were carried out using enclosures constructed from new, clear polyethylene tubing having a circumference of 1 metre and a wall thickness of 0.10 mm. The isolated volume of each enclosure was 260 litres. Ten of the enclosures were bags and the remainder, columns. The upper end of each tube and the lower end of each column was held open by clamping the tubing between two bands of galvanized metal in such a way that the metal was outside the enclosure. The lower end of each column was wedged into the bottom muds whereas the lower end of the bags was not, having been sealed. Depth of water within each enclosure was three metres. The enclosures were suspended from a securely anchored framework suspended on floats.

Composite sampling of the enclosures to a depth of 2.5 metres was accomplished using a length of 5 cm diameter acrylic tubing fitted with a foot valve. The entire sample was then discharged via a side delivery tube into a clean opaque glass container. Aliquots of both filtered and raw water for chemical analyses were placed in sterile polyethene bags and frozen. Other subsamples were obtained for determination of chlorophyll a, phytoplankton, rotifer and crustacean populations, and treated as described earlier. Identification of the latter were based on descriptions of Ward and Whipple (1965).

The photosynthetic activity of the phytoplankton was determined by exposing one of two aliquots, treated with $NaHCO_3$-^{14}C, to a light intensity of 5000 lux provided by a bank of Sylvania Cool White Power Tube fluorescent lamps.

The other aliquot was placed in darkness. After 4 hours the samples were treated with HgCl (Johnson et al, 1968) and subsequently filtered and counted in the scintillation spectrometer.

Composite carbon dioxide, alkalinity, and pH measurements were obtained by sampling each enclosure with a 3 metre tube, 1 cm diameter. Titrations were carried out immediately.

At the end of the study, which began in early July and lasted for a period of four weeks, the enclosures were recovered. A representative sample of the materials present on the interior walls was then obtained by gently siphoning an area of 20 cm by 3 metres, 20 percent of the wall area, and preserving the slurry with Lugol's solution.

The dry weight of sestonic and periphytic solids were determined by gently filtering aliquots of concentrates through a 25 mm 0.45 u membrane which had been previously washed with distilled water, dried overnight at 75^{o}C and then allowed to stabilize at room temperature for one hour in a dessicator before being weighed. Filtered samples were treated as described above and the dry weight corrected relative to changes in identically treated control membranes. (Strickland and Parsons, 1968)

The various fertilization treatments used in the enclosure study are listed in Table I. Enclosures fed only at the beginning of the experiment are indicated by an asterisk(*), all other tubes were fed daily after sampling.

TABLE I

Fertilization Treatments to Enclosures

Carbon as Glucose, Nitrogen as NH_4NO_3, Phosphorus as NaH_2PO_4

Enclosure	Treatment	Carbon	Nitrogen	Phosphorus
Bag	B-Control			
	B-N*		784 µg/l	
	B-P*			56 µg/l
	B-NP*		784 µg/l	56 µg/l
	B-C*	2036 µg/l		
	B-CNP*	2036 µg/l	784 µg/l	56 µg/l
	B-NP		28 µg/l	2 µg/l
	B-2C	74 µg/l		
	B-2CNP	74 µg/l	28 µg/l	2 µg/l
Columns	C-Control			
	C-NP*		784 µg/l	56 µg/l
	C-C*	2036 µg/l		
	C-CNP*	2036 µg/l	784 µg/l	56 µg/l
	C-1C	7 µg/l		
	C-2C	74 µg/l		
	C-3C	740 µg/l		
	C-1CNP	7 µg/l	28 µg/l	2 µg/l
	C-2CNP	74 µg/l	28 µg/l	2 µg/l
	C-3CNP	740 µg/l	28 µg/l	2 µg/l

* These treatments fed once at the beginning of the experiment, all other treatments were fed the above amounts daily

RESULTS

LAKE LIMNOLOGY

Physical and Chemical Characteristics

Secchi disc measurements of water transparency from May to October 1971, 1972 (Figure 2) ranged from 3 to 6 metres with mean depth values in each year of 5.0 and 4.8 metres respectively. The depth of the one percent isophot in 1972 is also indicated.

Changes in water temperature during these periods (Figure 3) show penetration of the 20°C isotherm to have been deeper in 1971 than 1972 although the maximum depth attained by the 15°C isotherm was more or less comparable - 7 metres. The 10°C isotherm was also deeper in 1971 than 1972.

Dissolved oxygen concentrations in early May were more or less homogeneous with depth (Figure 4) and remained in excess of 5 mg/l to depths of about 12 metres throughout most of the study period. At one metre above the bottom the oxygen content of the water was never observed to be less than 3 mg/l.

The average, minimum and maximum values obtained for various chemical parameters from sampling to a depth of 15 metres are presented in Table II. Seasonal depth changes of dissolved silicate, organic carbon, nitrogen and phosphorus are displayed in Figure 5.

Phytoplankton

Profiles of phytoplankton standing crops (mm^3/l) showing variation in the community structure with depth and time are depicted in Figure 6. The maximum density observed

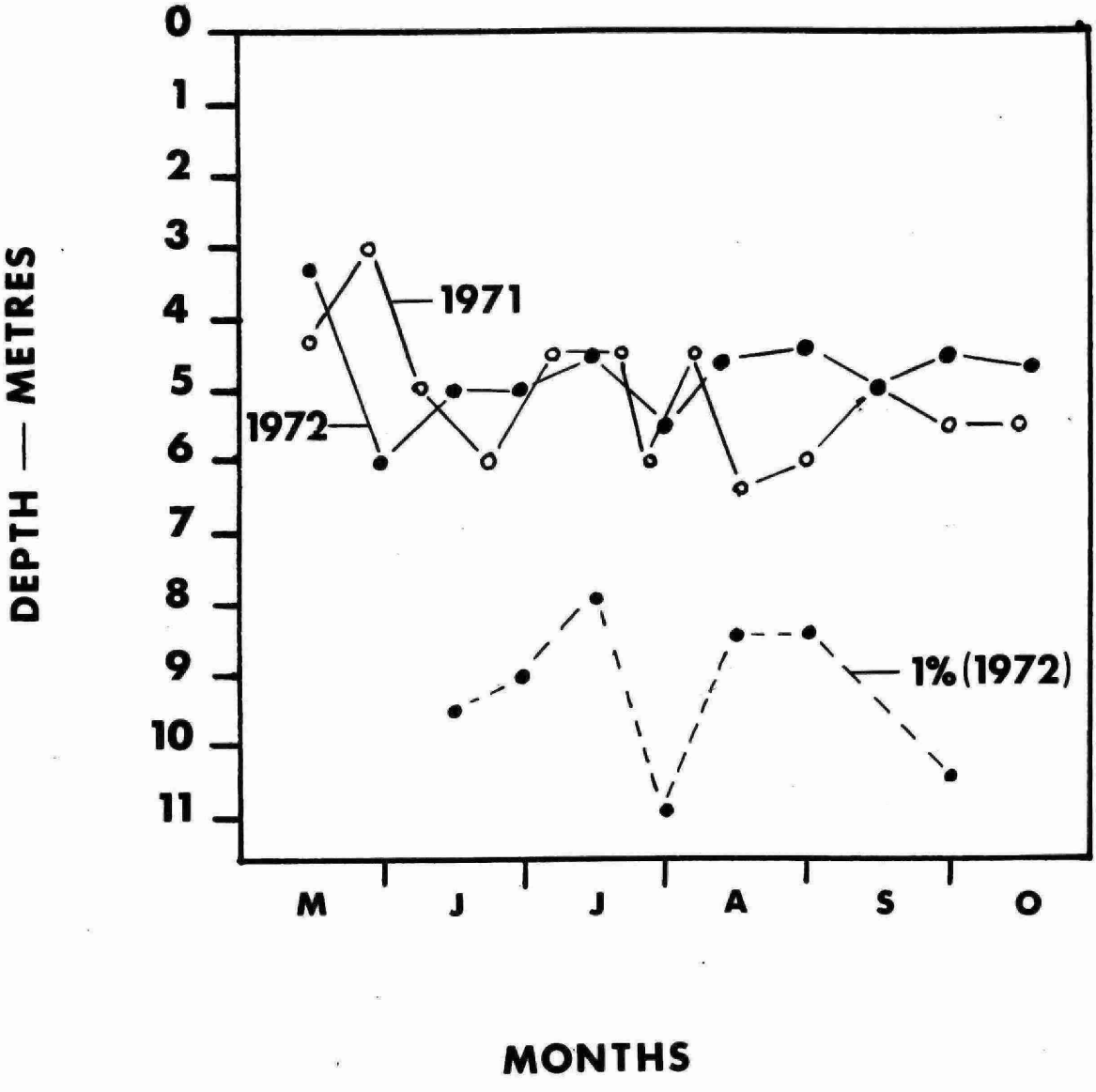

Figure 2

Secchi disc measurements of water transparency in 1971, 1972 and the depth of the 1% isophot in 1972.

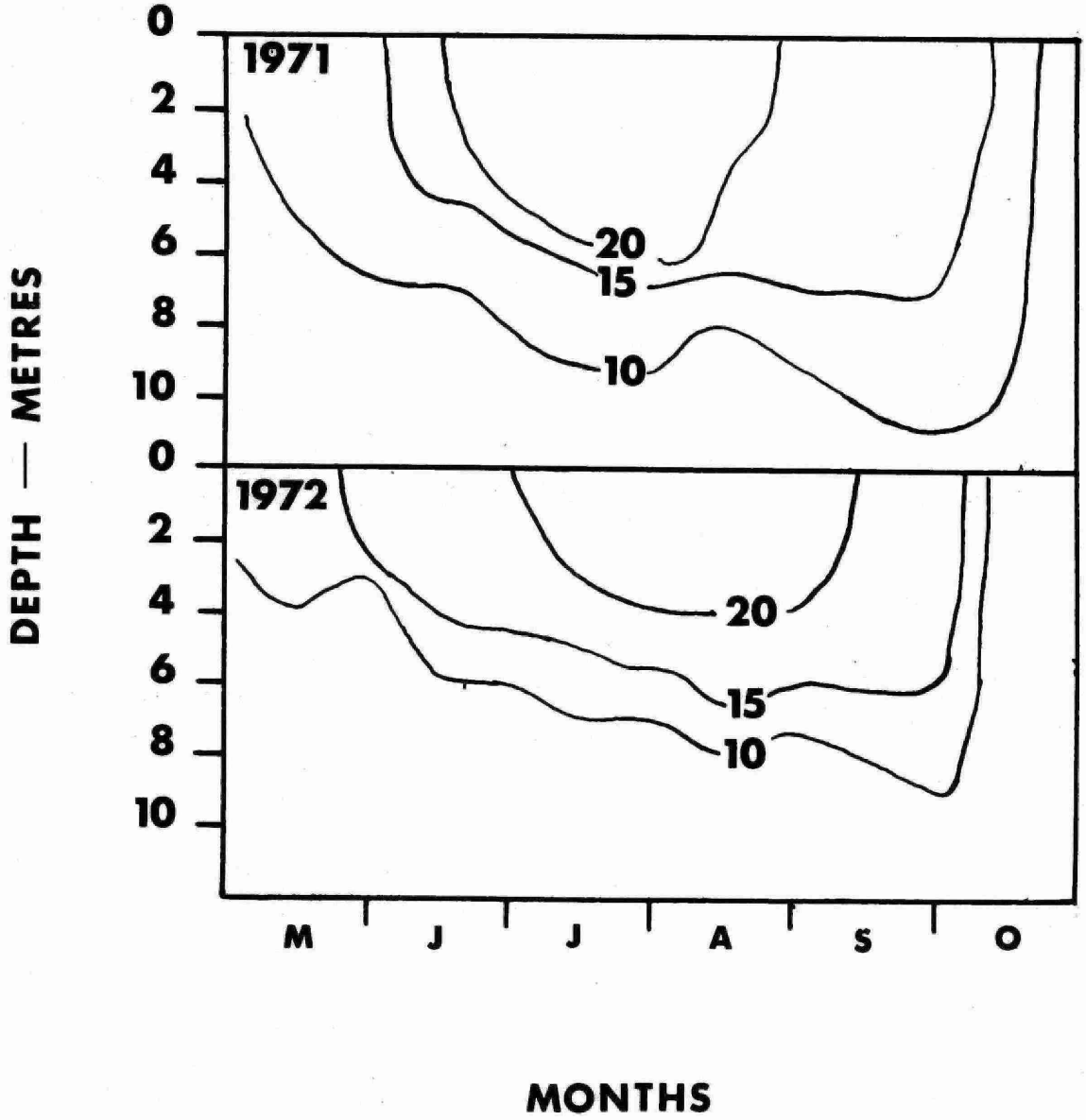

Figure 3

Seasonal depth variations in water temperature in 1971, 1972 (5°C isotherms).

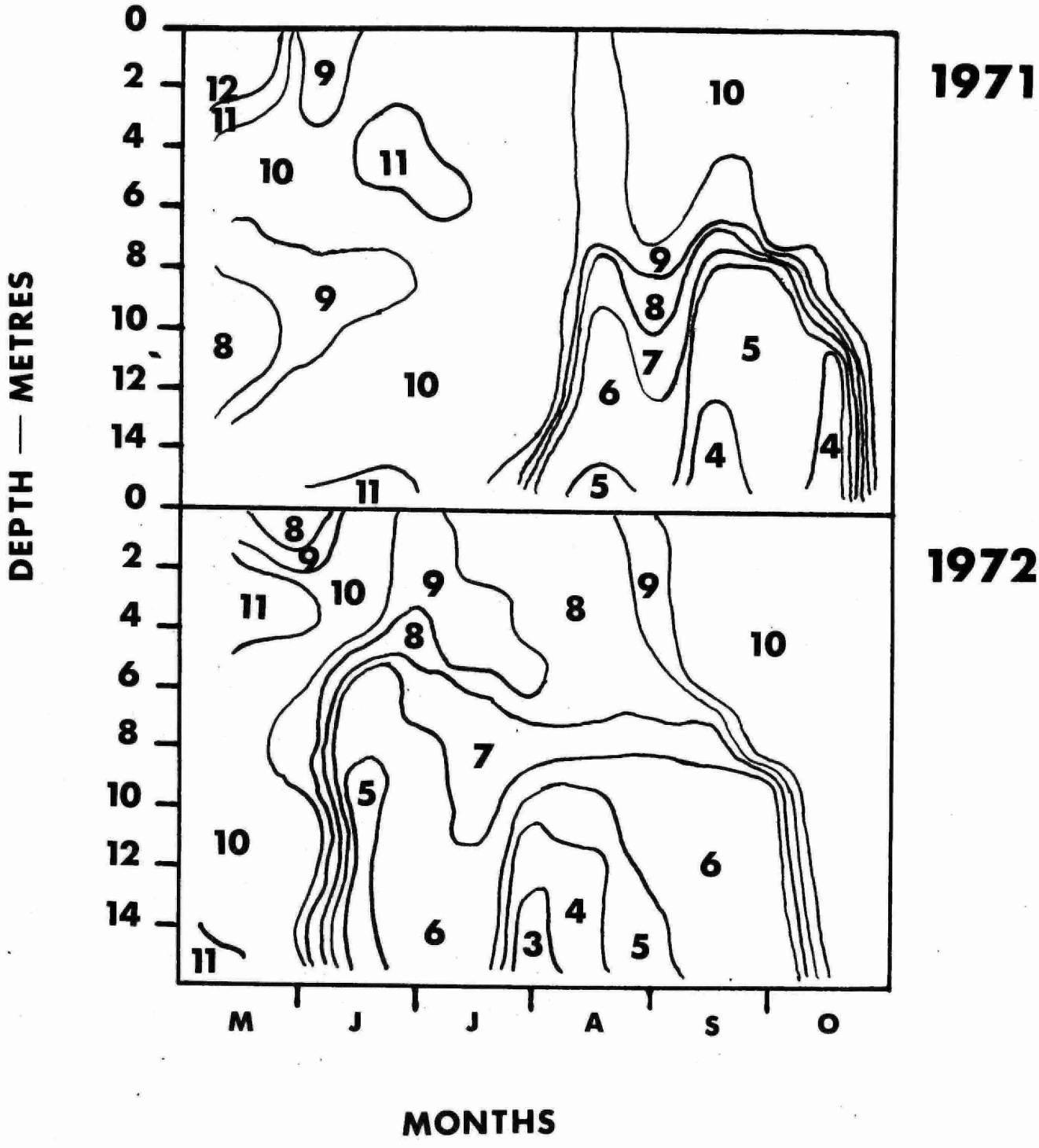

Figure 4

Seasonal depth variations of dissolved oxygen (mg/l) in 1971, 1972.

TABLE II

Water Chemistry of Kushog Lake in 1971, 1972

Parameter		1971			1972		
		Mean	Range	Obs.	Mean	Range	Obs
Calcium	mg/l	4	4 - 5	36		3 - 6	66
Magnesium	mg/l	1	1	36		1 - 3	66
Sodium	mg/l	2	1 - 3	36		1 - 2	66
Potassium	mg/l	0.6	0.5 - 0.8	36	0.4	0.1 - 0.7	66
Total Iron	mg/l	0.07	0.00 - 0.40	36	0.10	0.05 - 0.20	66
Sulphate	mg/l	9	5 - 12	36		5 - 40	66
Chloride	mg/l	4	1 - 4	30		2 - 5	54
Manganese	mg/l	0.03	0.00 - 0.15	30	0.02	0.01 - 0.27	66
Dissolved Solids	mg/l	43	25 - 100	36		20 - 70	54
Conductivity	mhos/cm^3	40	39 - 42	24		38 - 43	42

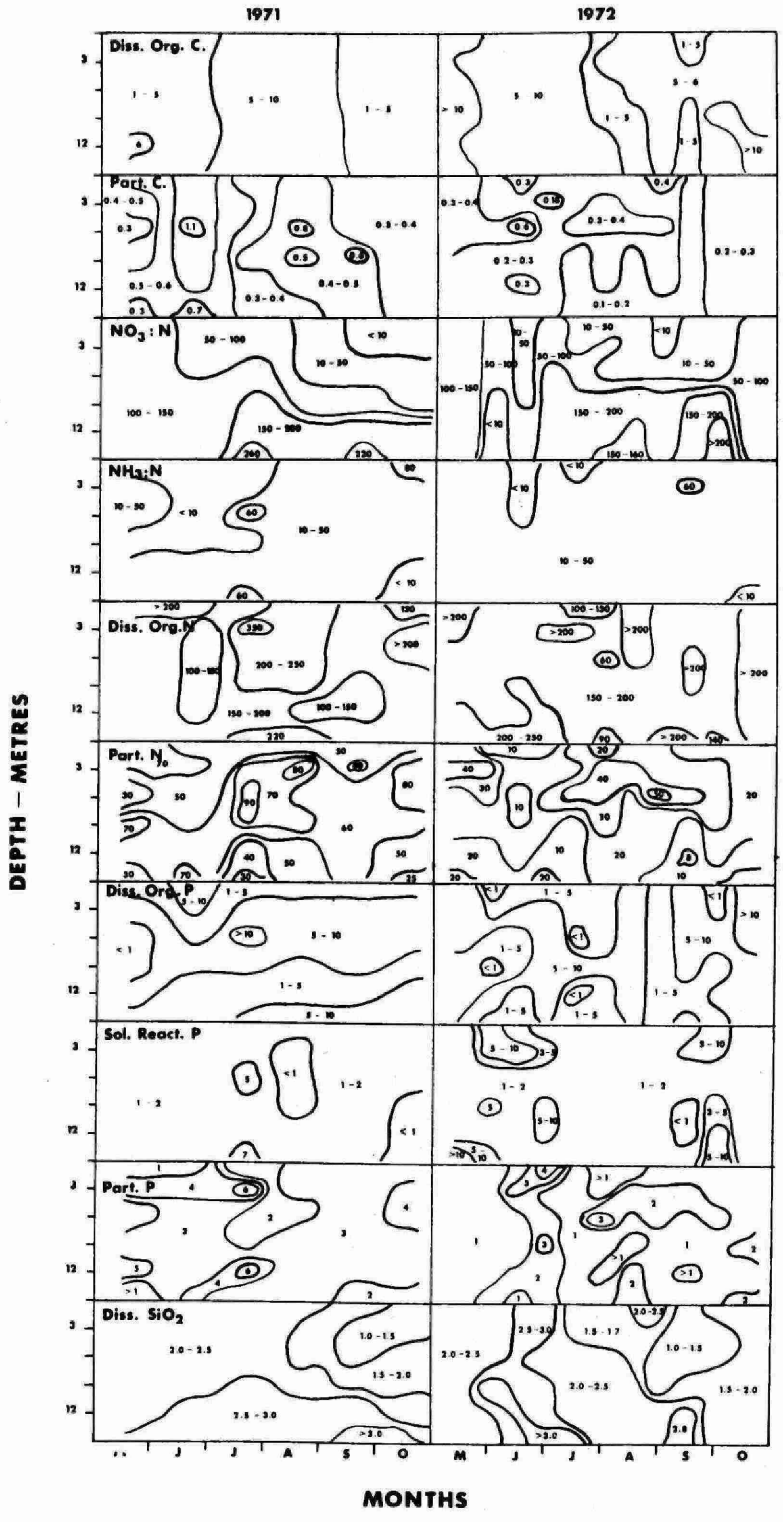

Figure 5

Seasonal depth variations in 1971, 1972 of dissolved organic carbon (mg/C/l), particulate carbon (mg/C/l), nitrate nitrogen (µg N/l), ammonia (µg N/l), dissolved organic nitrogen (µg N/l), particulate nitrogen (µg N/l), dissolved organic phosphorus (µg P/l), soluble reactive phosphorus (µg P.l), particulate phosphorus (µg P/l) and dissolved silicate (mg SiO_2/l).

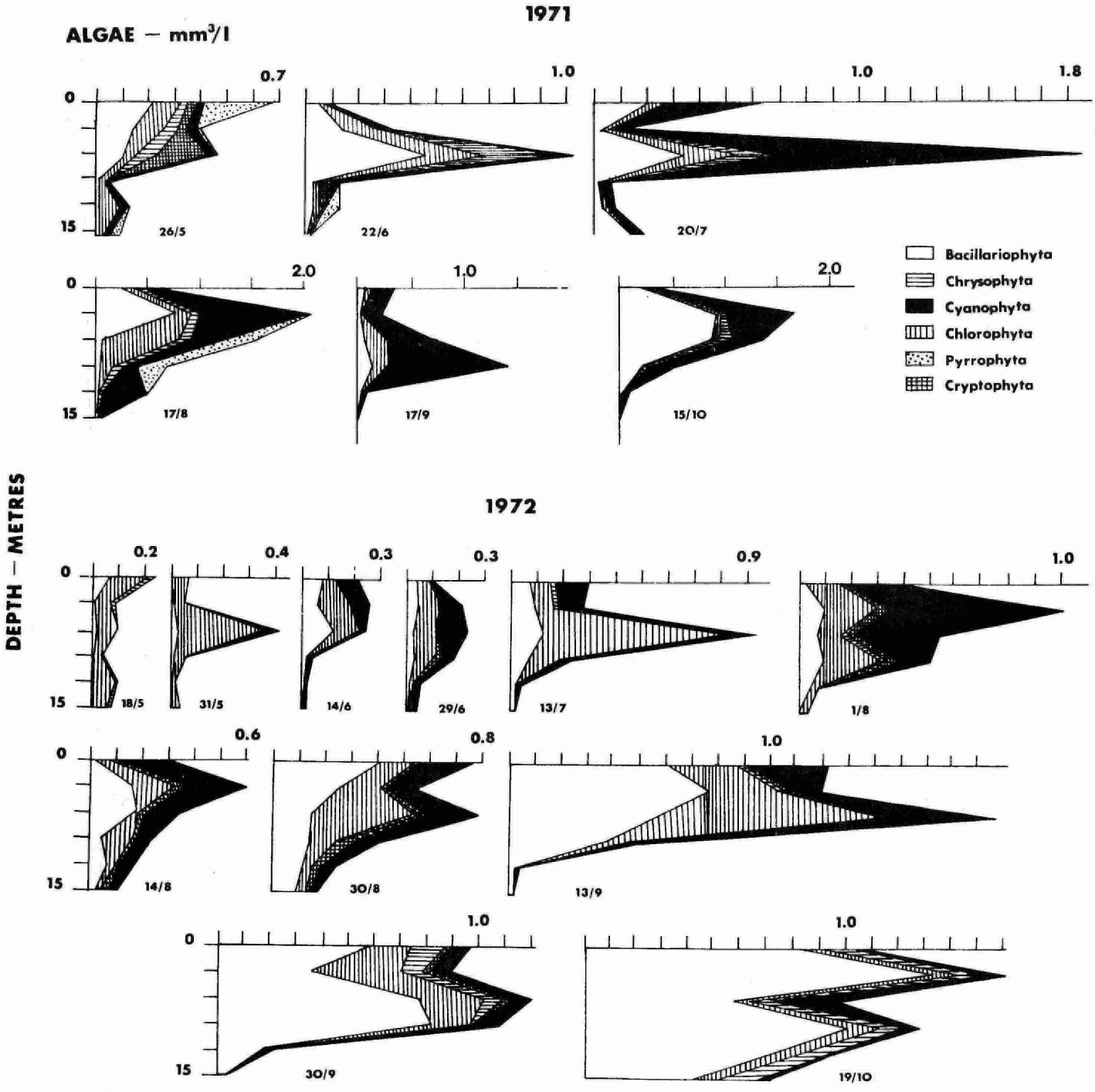

Figure 6

Profiles of phytoplankton standing crops (mm^3/l) during 1971, 1972.

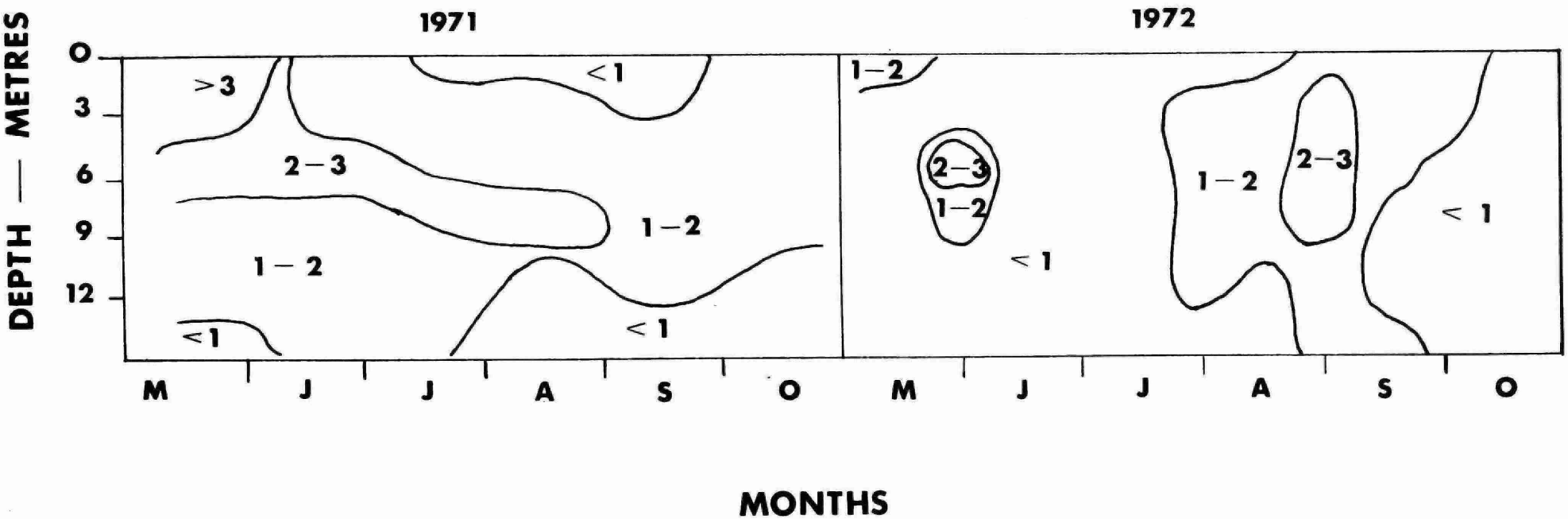

Figure 7

Seasonal depth variations of chlorophyll a (µg/l) during 1971, 1972.

in each year did not exceed 2.0 mm^3/l. Chlorophyll a concentrations (µg/l) have been illustrated in Figure 7. Maximum quantities of this parameter never exceeded 3 µg/l.

The average percentage composition of the phytoplankton standing crops (Table III) indicates the Bacillariophyta to have remained more or less uniform between years, the Cyanophyta declining in dominence from 1971 to 1972 and being replaced primarily by the Chlorophyta. A list of phytoplankters encountered during the study is presented in Table IV.

Profiles of monthly assessments of phytoplankton primary productivity displayed in Figure 8 are based on 4 hours exposures and then expressed as mg $C/m^3/day$, the daylength being the period between sunrise and sunset. Planimetric estimates of carbon fixation per unit area per day (mg $C/m^2/day$) have been included. The most productive period in 1971 appears to have occurred toward the end of the summer, in September and October, whereas in 1972 highest productivities were obtained in May and June.

LABORATORY EXPERIMENT: 1970

Samples of lake water were obtained in April, 1970 from a depth of 1 - 5 metres below an ice cover approximately 70 cm. thick. Chemical characteristics of the lake water are indicated in Table V. Aliquots were enriched with nitrogen and/or phosphorus and cultured at the laboratory for a period of three weeks, phytoplankton responses being assessed at weekly intervals on the basis of chlorophyll a determinations (Figure 9). The greatest response was obtained on the third week from the combined addition of nitrogen and

TABLE III

The Average Percentage Composition of Phytoplankton Standing Crops in 1971, 1972

	1971	1972
Bacillariophyta	32.9	39.8
Chlorophyta	16.6	34.1
Chrysophyta	3.2	7.7
Cryptophyta	2.5	5.2
Cyanophyta	41.2	12.8
Euglenophyta	1.6	0.3
Pyrrophyta	2.0	0.1

TABLE IV

Phytoplankton of Kushog Lake

BACILLARIOPHYTA

Achnanthes inflata Kuetzing

Achnanthes minutissima (Kuetzing) Cleve

Amphipleura pellucida Kuetzing

Amphora spp.

Asterionella formosa Hassall

Caloneis amphisbaena (Bory) Cleve

Cocconeis diminuta Ehrenberg, Grunow

Cyclotella bodanica Eulenstein

Cymbella ventricosa Kuetzing

Fragilaria capucina Desmazieres

Fragilaria crotonensis Kitton

Gomphonema spp.

Melosira islandica Muller

Navicula spp.

Nitzchia spp.

Stauroneis phoenicentron (Nitzsch) Ehrenberg

Stephanodiscus niagare Ehrenberg

Synedra rumpens Kuetzing

Tabellaria fenestrata (hyngb.) Kuetzing

Tabellaria flocculosa (Roth) Kuetzing

CHLOROPHYTA

Ankistrodesmus falcatus (Corda) Ralfs

Arthrodesmus spp.

Table IV - cont'd

Asterococcus spp.

Botryococcus braunii Kuetzing

Chaetosphaeridium

Characium spp.

Chlamydomonas spp.

Chlorella vulgaris Beyerinck

Chlorococcum humicola (Naegeli) Rabenhorst

Coelastrum spp.

Cosmarium spp.

Crucigenia apiculata (Lemmermann) Schmidle

Crucigenia rectangularis (Naegeli) Gay

Dictyosphaerium Ehrenbergianum Naegeli

Dictyosphaerium pulchellum Wood

Elakatothrix spp.

Euastrum spp.

Haemotococcus lacustris (Girod) Rostafinski

Kirchneriella spp.

Micrasterias spp.

Mougeotia spp.

Oocystis borgei Snow

Oocystis elliptica W. West

Pediastrum duplex Meyen

Pediastrum tetra (Ehrenberg) Ralfs

Pyranimonas tetrarhynchus Schmarda

Quadrigula lacustris (Chodat) Smith

Scenedesmus bijuga (Turpin) Lagerheim

Scenedesmus quadricauda (Turpin) Brebisson

Schroederia setigera (Schroeder) Lemmermann

Sphaerocystis spp.

Staurastrum spp.

Tetraedon minimum (Braun) Hansgirg

Tetraedon muticum (Braun) Hansgirg

Tetrastrum spp.

Treubaria setigerum (Archer) Smith

CHRYSOPHYTA

Chlorochromonas minuta Lewis

Diachros simplex Pascher

Dinobryon bavaricum Imhof

Dinobryon sertularia Ehrenberg

Gloeobotrys limneticus (Smith) Pascher

Mallomonas spp.

Ophiocytium capitatum Wolle

CYANOPHYTA

Anabaena circinalis Rabenhorst

Anabaenopsis spp.

Aphanocapsa spp.

Apnanothese clathrata West & West

Coelosphaerium pallidum Lemmermann

Chroococcus dispersus (Keissl) Lemmermann

Chroococcus limineticus Lemmermann

Chroococcus minor (Kuetzing) Naegeli

Dactylococcopsis ocicularis Lemmermann

Gloeocapsa spp.

Gloeothece rupestris Lyngbye

Gomphosphaeria aponina Kuetzing

Gomphosphaeria lucustris Chodat

Merismopedia spp.

Microcystis aeruginosa Kuetzing

Oscillatoria spp.

Phabdoderma lineare Schmidle and Lauterborn

CRYPTOPHYTA

Cryptomonas erosa Ehrenberg

Euglenophyta

Euglena minuta Prescott

Euglena sanguinea Ehrenberg

Lepocinclis spp.

Phacus spp.

Trachelomonas spp.

PYRROPHYTA

Ceratium hirundinella (Muell) Dejardin

Chroomonas Nordstedtii Hansgirg

Glenodium spp.

Hemidinium nasutum Stein

Hemidinium limbatum (Stokes) Lemmermann

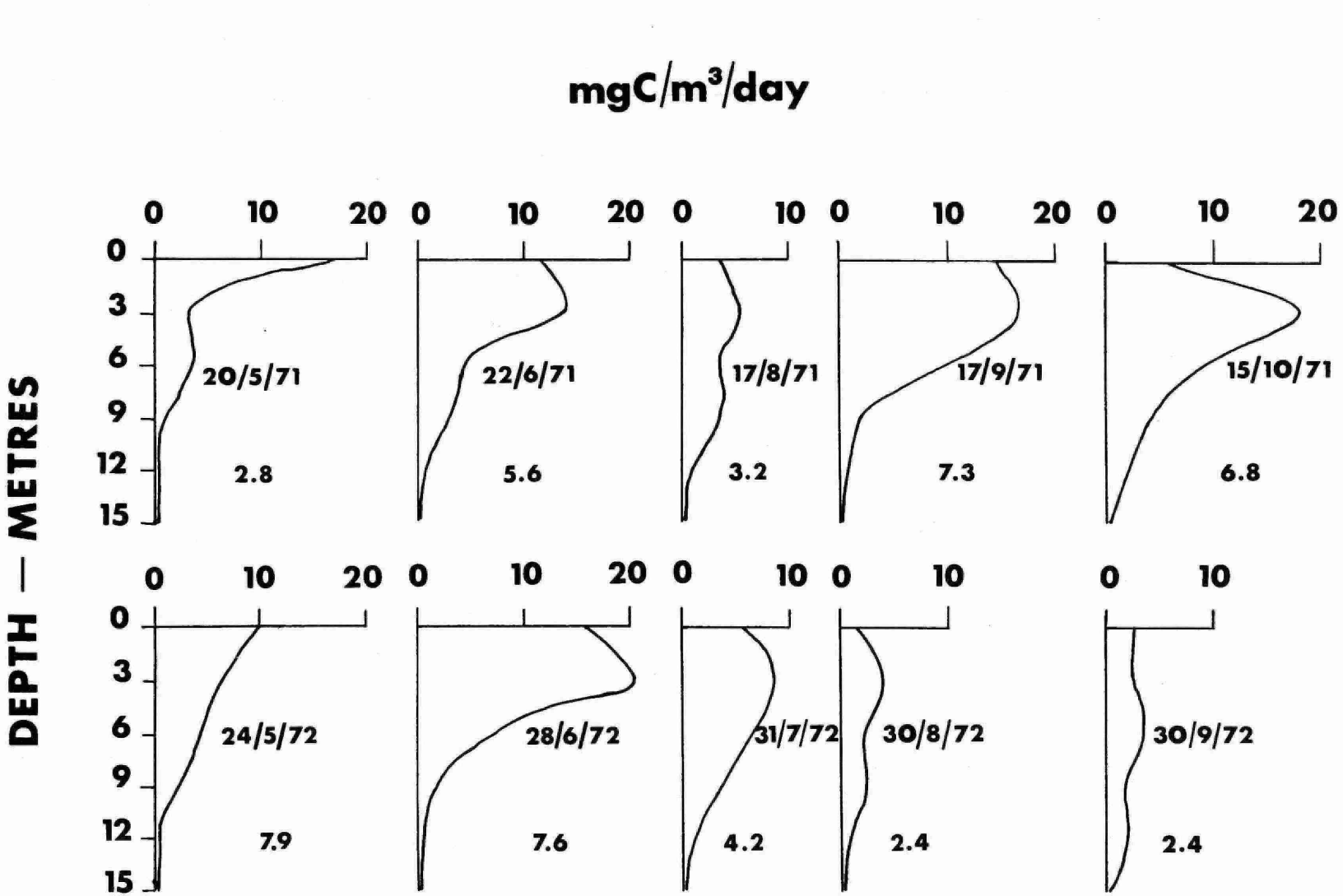

Figure 8

Profiles of phytoplankton productivity per unit volume (mg C/m^3/day) and per unit area (mg C/m^2/day) at monthly intervals during 1971, 1972.

TABLE V

Chemistry of Late Winter Water Sample
Used in the Laboratory Enrichment Experiment

Calcium	5 mg/l
Magnesium	2 mg/l
Dissolved SiO_2	4.1 mg/l
Alkalinity (as $CaCO_2$)	5 mg/l
Total Phosphorus	20 ug/l
Total Nitrogen	1027 ug/l
Nitrate N	600 ug/l
Nitrite N	7 ug/l
Ammonia N	230 ug/l

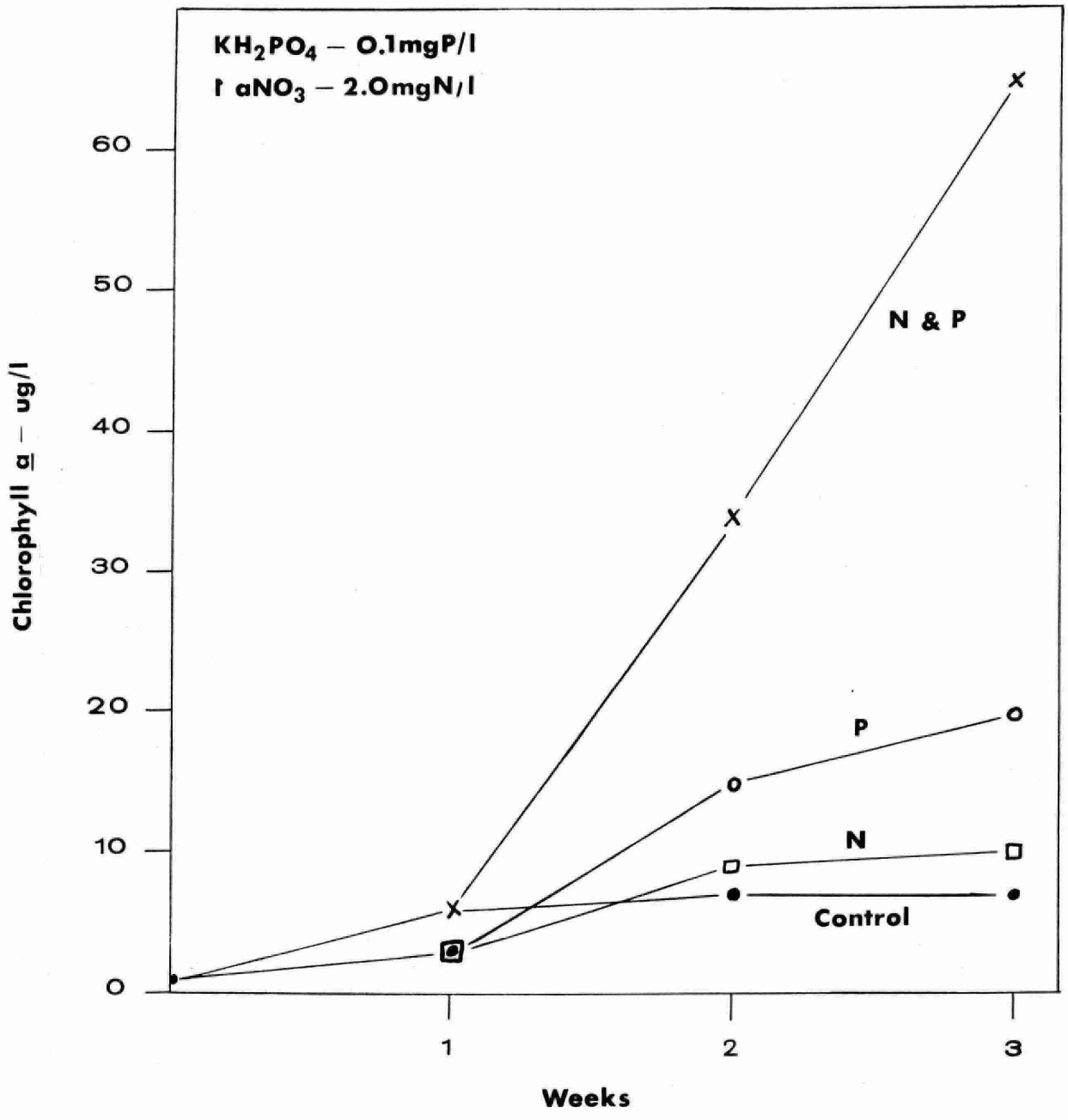

Figure 9

Phytoplankton responses (chlorophyll a - µg/l) in laboratory cultures of under-ice Kushog Lake water enriched with nitrogen and/or phosphorus.

phosphorus, the chlorophyll level of 65 µg/l, being several fold greater than the sum of the maximum responses associated with enrichment of only nitrogen or phosphorus.

FIELD TRIAL FERTILIZATION EXPERIMENTS

Biomass

The highest phytoplankton concentration observed during the field trial study, 4050 mm^3/l, occurred in the bag enclosure receiving a single feeding of glucose, nitrogen and phosphorus (B-CNP*) (Figure 10) and was about eight to ten times greater than values recorded from either the control (B-Control) or adjacent lake water. Of the various sytems receiving single feedings of carbon (B-C*, C-C*), nitrogen (B-N*), or phosphorus (B-P*), only in the latter did a maximum phytoplankton concentration develop in excess of its control (B-Control or C-Control). The combined addition of a single feeding of nitrogen and phosphorus in a bag enclosure (B-NP*) developed a maximum no greater than when only phosphorus was added (B-P*) but greater than observed with an equivalent treatment in a column enclosure (C-NP*). Of the two treatments receiving single combined feedings of carbon nitrogen and phosphorus, the maximum algal quantity of the bag enclosure (B-CNP*) was more than twice its column counterpart (C-CNP*).

The total algal response obtained in each treatment, expressed on a per unit volume basis (Table VI), was calculated by adding together the terminal periphytic quantity of algae along with a planimetric estimate of the phytoplankton which developed over the 28 day study period. The most productive enclosure was the tube which received a single

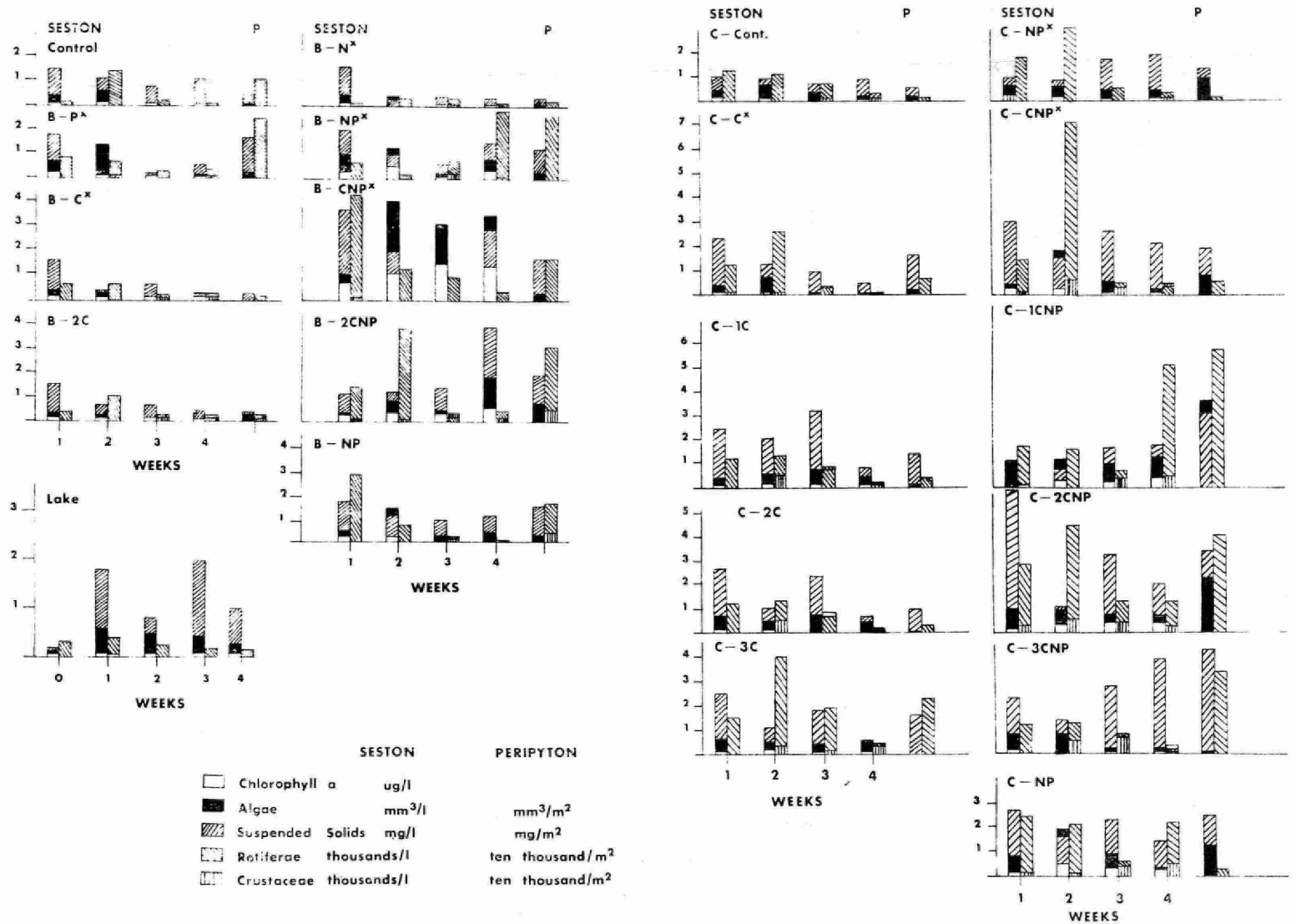

Figure 10

Characteristics of samples of weekly seston and terminal periphyton obtained from in situ isolated volumes of Kushog Lake water fertilized with glucose, nitrogen, phosphorus.

TABLE VI

Total Quantities of Suspended Solids, Algae and Animals (rotifers plus crustaceans) which Developed in the Enclosures Over 28 Days as calculated by Summing Planimetric Estimates of Suspended Materials Plus Terminal Periphytic Materials: Expressed per Unit Volume

Treatment	Suspended Solids mg/l	Algae mm^3/l	Animals thousands/l
B-Control	39	9	17
B-N*	22	6	10
B-P*	46	16	18
B-NP*	34	20	25
B-C*	21	6	12
B-CNP*	78	71	28
B-NP	43	17	40
B-2C	26	5	10
B-2CNP	37	17	30
C-Control	26	12	26
C-NP*	33	14	43
C-C*	39	8	31
C-CNP*	64	20	74
C-NP	58	27	52
C-1C	48	13	37
C-2C	42	15	40
C-3C	45	12	62
C-1CNP	39	30	54
C-2CNP	87	24	73
C-3CNP	177	15	23

feeding of carbon, nitrogen and phosphorus (B-CNP*), the total quantity of algae which developed being about three times greater than that obtained with a comparable nitrogen and phosphorus treatment lacking carbon (B-NP*). Total responses in bag enclosures to daily feeding of only carbon to the bag systems (B-C*; B-2C) resulted in the development of algal quantities less than the control (B-Control).

Within the column systems, single feedings of nitrogen and phosphorus, with or without glucose (C-NP*; C-CNP*), yielded algal responses slightly greater than their control tube (C-Control) but slightly less than accrued in comparable column systems fed daily (C-NP: C-2CNP), these latter being more or less equal.

Comparison of quantities of algae present on the last day of the study in those tubes receiving daily feedings of carbon and/or nitrogen plus phosphorus (Figure 11) indicates the largest algal population at that time to be present in the tube receiving nitrogen, phosphorus and the lowest glucose addition (C-1CNP), the algal biomass declining with increasing carbon loading (C-2CNP; C-3CNP).The solids of each of those enclosures receiving nitrogen and phosphorus appears to be quite comparable. Carbon feeding alone had no apparent stimulatory effect on either the development of algae or the rotifers and crustaceans. In those tubes which were fed nitrogen and phosphorus however, the animal populations display a relationship to the various treatments similar to that noted with the algae, though not as closely in the bag enclosures as with the columns.

The initial phytoplankton community (Figure 12)

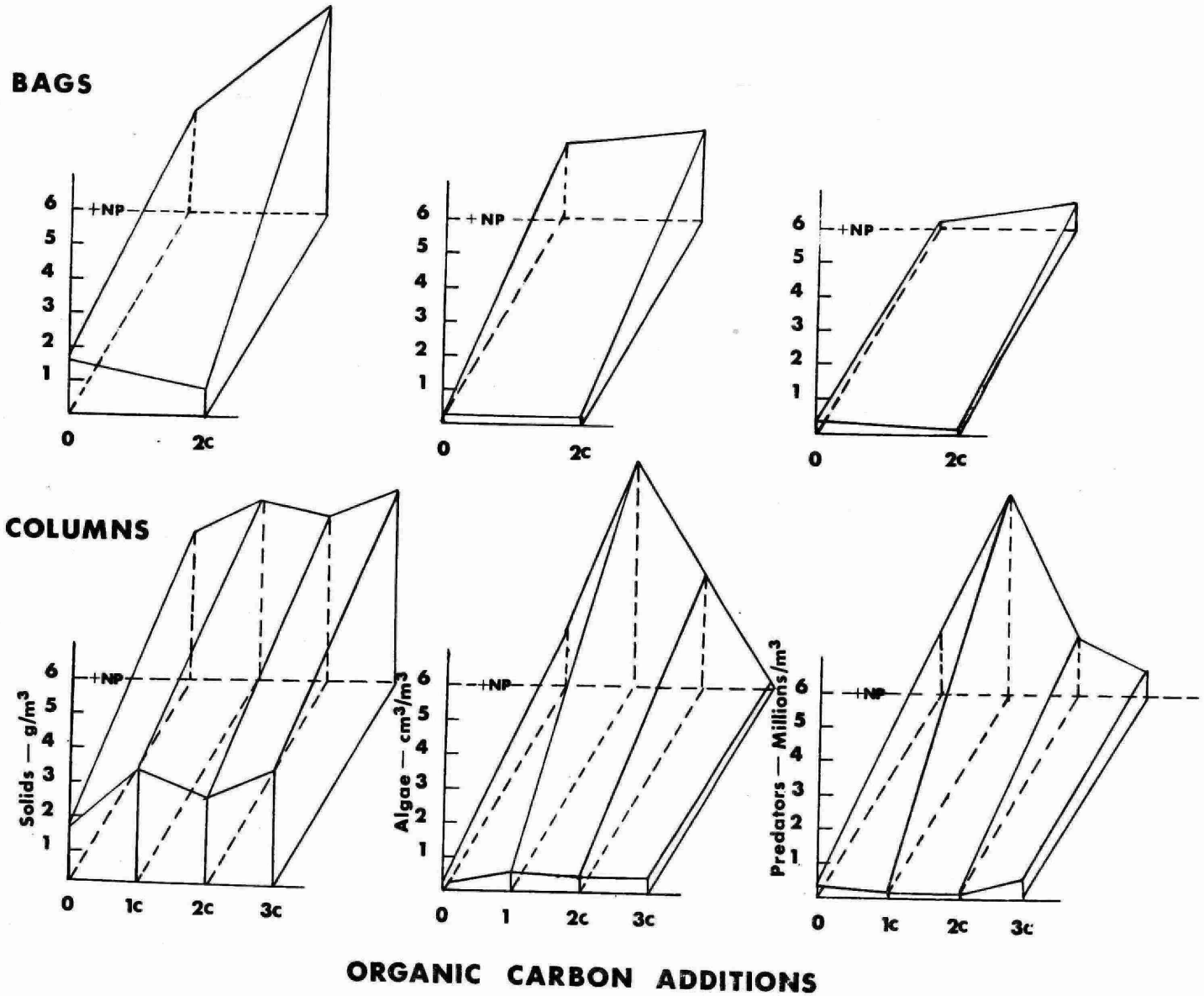

Figure 11

The solids, algae and rotifers plus crustaceans associated with the seston plus periphyton on the 28th day of those enclosures receiving daily additions of glucose and/or nitrogen plus phosphorus.

consisted of nearly equal quantities of Bacillariophyta, Chlorophyta and Cyanophyta, the dominant forms including Cyclotella spp., Stephanodiscus spp.. The more predominant phytoplankton genera observed in the communities of the various enclosures are listed in Table VII.

Within each bag enclosure the Chlorophyta exceeded a 50 percent domination of the community at some time during the study and the Bacillariophyta, never. Four treatments where the Cyanophyta exceeded this percentage include B-Control, B-N*, B-2C, and B-2CNP. In this latter system algae representing types other than associated with the above gained prominence due to the abundance of a form of Chrysophyta - Chrysidiastrum spp..

Within the column enclosures the Chlorophyta attained a 50 percent level in only four systems - C-Control, C-NP*, C-NP, and C-3CNP. On the other hand the diatoms dominated at this level in all but four systems at some time during the investigation, two of which C-Control and C-3CNP along with C-1C and C-3C, had a population which shifted to mainly bluegreen or Cyanophyta.

The composition of the terminal periphytic communities is also illustrated and shows a domination by the Bacillariophyta in all but three systems, the Chlorophyta making up the largest population in tubes B-CNP*, B-2C, and C-C*.

Photosynthetic Activity

Algal populations displaying the highest rates of net carbon assimilation were obtained with samples from

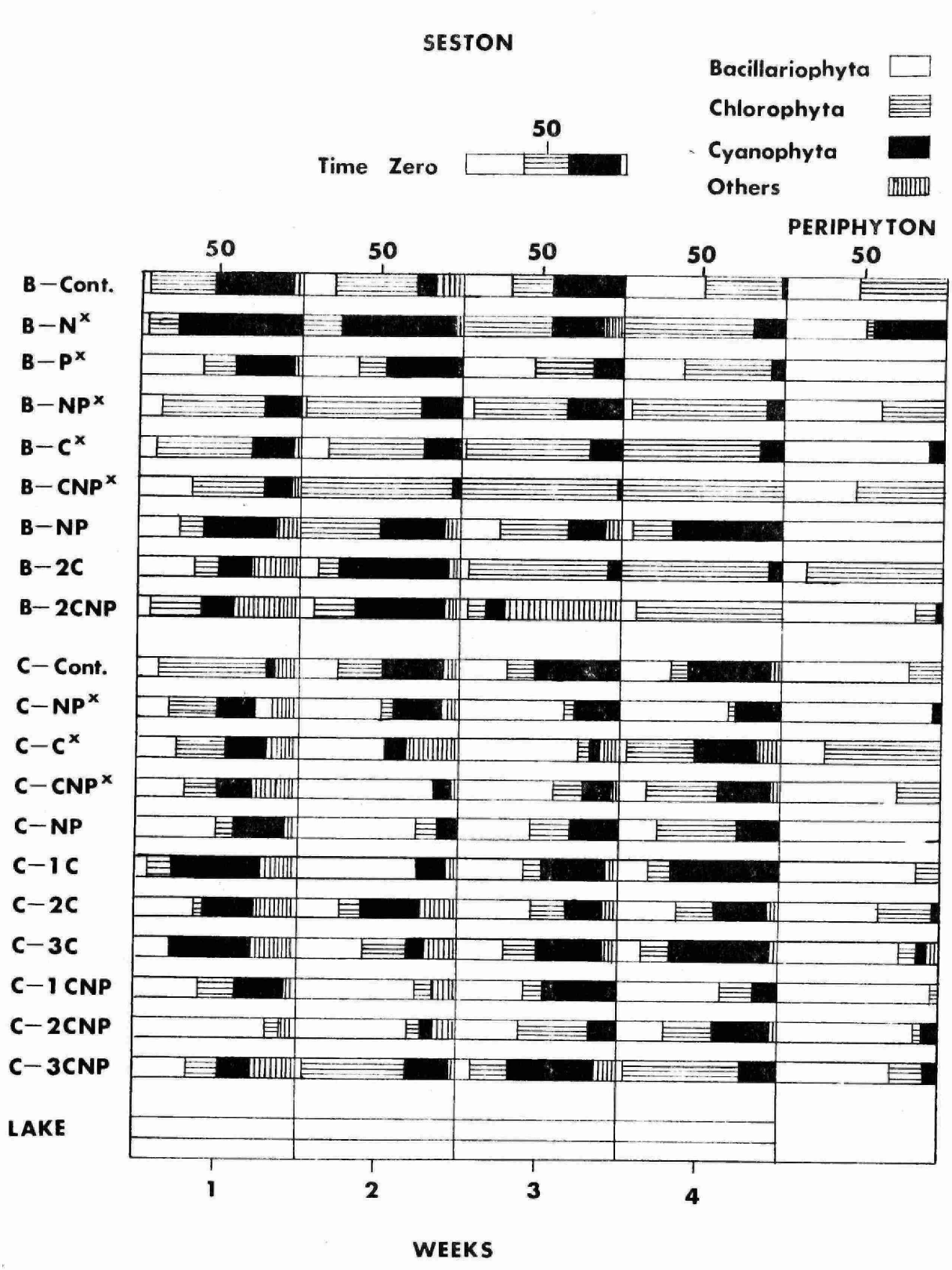

Figure 12

Percentage composition of phytoplankton standing crops at weekly intervals and the algal community of the terminal periphyton associated with the enclosures of the fertilization field study.

TABLE VII

Predominant Forms of Phytoplankton Associated With the Enclosures of the Field Experiments

	C-Control	C-NP*	C-C*	C-CNP*	C-NP	C-1C	C-2C	C-3C	C-1CNP	C-2CNP	C-3CNP
BACILLARIOPHYTA											
Asterionella	X	X	X	X	X	X	X	X	X	X	X
Fragilaria									X		
Melosira				X		X					
Navicula						X					
Nitzchia		X		X	X				X	X	
Tabellaria							X		X	X	
CHLOROPHYTA											
Botryococcus	X		X		X			X			X
Chlamydomonas									X		
Cosmarium				X	X						
Euastrum	X				X					X	
Oocystis						X					
Scenedesmus					X	X	X				
Staurastrum	X						X		X		
CHRYSOPHYTA											
Dinobryon		X					X	X		X	X
CYANOPHYTA											
Chroococcus	X							X		X	X
Coelosphaerium	X										
Gloeocapsa					X						
Oscillatoria					X				X	X	

Table VII - Cont'd

	B-Control	B-N*	B-P*	B-NP*	B-C*	B-CNP*	B-NP	B-2C	B-2CNP
BACILLARIOPHYTA									
Asterionella	X		X		X	X		X	X
Cyclotella					X				
Navicula		X							
Nitzchia			X				X		
Tabellaria	X								
CHLOROPHYTA									
Ankistrodesmus			X	X	X	X	X	X	X
Arthrodesmus					X				
Botryococcus	X	X			X		X	X	X
Chlamydomonas				X					X
Chlorella					X	X			
Cosmarium	X				X				
Euastrum					X		X	X	
Oocystis	X								
Pediastrum			X	X					
Quadrigula				X	X				
Scenedesmus		X		X	X	X			X
CHRYSOPHYTA									
Chrysidiastrum							X		X
Dinobryon							X	X	
CYANOPHYTA									
Aphanocapsa	X			X	X				
Aphanothece	X	X	X						
Chroococcus		X	X	X	X				
Coelospharium			X						
Gomphosphaeria	X	X	X		X				

tube B-CNP* followed by B-NP* (Table VIII). Responses associated with samples from both controls and B-N*, appeared to have maximized by the second week as did those of enclosures to which daily feedings of only carbon were added other than C-3C. Responses within those systems which received daily additions of nitrogen and phosphorus with or without carbon, excluding C-3CNP, did not attain their highest observed rate of uptake until at least the third week.

From the above data a planimetric estimate of the overall net photosynthetic carbon uptake over the four week period was determined and these values divided by a similar estimate of the phytoplankton population. The results of these calculations yield a sort of overall Production/Biomass Index for each enclosure. Index values were found to range from about 3 - 61 mg C/4 hours/cm^3, tubes B-Control and C-Control being 9 and 8 respectively. (Figure 13). The highest index value was found to be associated with treatment B-NP*, B-CNP* being second. Of the bags and columns receiving comparable nutrient additions the index associated with a bag enclosure exceeded that of its column counterpart. Within the columns, daily additions of carbon along with nitrogen and phosphorus in each case resulted in a higher index value than was obtained from column C-NP.

Temperature, Oxygen, Carbon Dioxide and pH

The results of weekly monitoring of the tubes and adjacent lake water before midday with respect to the temperature and dissolved oxygen concentrations at a depth

TABLE VIII

Weekly measurements of net photosynthetic activity as determined under artificial illumination (mg $C/m^3/4$ hours).

	Weeks			
Treatment	1	2	3	4
B-Control	5	2	2	1
B-N*	3	3	6	1
B-P*	4	12	6	2
B-NP*	100	55	29	7
B-C*	3	2	1	1
B-CNP*	70	145	143	86
B-NP	17	25	8	29
B-2C	3	3	1	2
B-2CNP	6	8	25	40
C-Control	8	2	2	1
C-NP*	10	5	3	2
C-C*	1	1	1	1
C-CNP*	6	6	7	4
C-NP	11	16	22	6
C-1C	6	8	3	2
C-2C	7	5	3	2
C-3C	7	5	2	1
C-1CNP	19	13	20	14
C-2CNP	10	16	28	10
C-3CNP	13	14	5	1

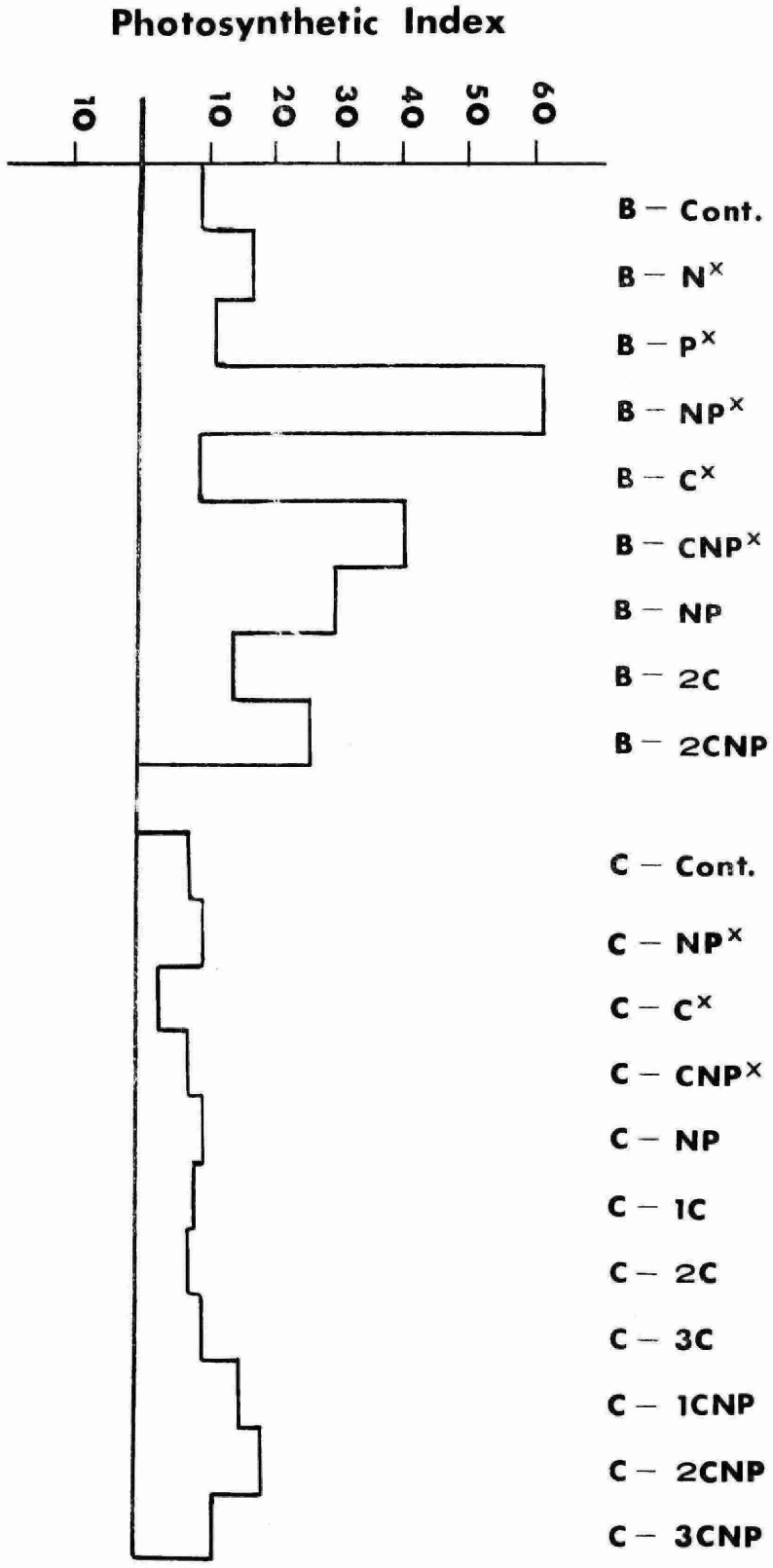

Figure 13

A Production/Biomass Index for each experimental treatment: net carbon uptake (mg C/m^3/4 hours)/ phytoplankton concentration (cm^3/m^3) integrated over a period of 28 days.

of 2.5 metres, and the total inorganic carbon content (expressed as $\mu MCO_2/l$) and pH of a composite sample from each enclosure are detailed in Table IX.

The dissolved oxygen content at this depth was never found to be less than 50 percent saturation in any enclosure.

The total inorganic carbon concentration, expressed as $\mu M\ CO_2/l$, of the adjacent lake water ranged from 168 - 227 $\mu M\ CO_2/l$ and the pH from 5.7 to 6.0. Within the enclosures the lowest free carbon dioxide quantity recorded, which would represent CO_2 plus H_2CO_3, was 45 $\mu M\ CO_2/l$ and that of total inorganic carbon was 125 $\mu M\ CO_2/l$. The pH fluctuated only slightly between enclosures ranging from between 5.6 and 6.2 though values as high as 7.0 were obtained from system B-CNP*.

Three days before the study was terminated six of the enclosures, which received daily feedings of nutrients, were monitored over a 24 hour period at 6 hour intervals. Observations began at midday following feeding. By late afternoon (Figure 15) the free carbon dioxide had disappeared in two of the systems at a time when the pH had increased in excess of 8.3. By the following morning, just before sunrise, the pH of treatment C-2CNP, for example, had decreased 2.2 units to 6.4 and the free carbon dioxide concentrations risen to 58 $\mu M\ CO_2/l$. Although the pattern of responses were somewhat similar in bag and column enclosures of comparable treatments, the magnitude of fluctuation in the latter was much greater.

TABLE IX

WEEKLY VARIATIONS OF

DISSOLVED OXYGEN, pH, CARBON DIOXIDE (MCO_2) and INORGANIC CARBON (ΣMCO_2)

WEEKS	1				2				3				4			
TREATMENT	DO mg/l	pH	CO_2 uM/l	ΣCO_2 uM/l	DO mg/l	pH	CO_2 uM/l	ΣCO_2 uM/l	DO mg/l	pH	CO_2 uM/l	ΣCO_2 uM/l	DO mg/l	pH	CO_2 uM/l	$\Sigma\Sigma CO_2$ uM/l
B-Cont	7.6	6.0	116	260	7.0	5.6	91	189	8.4	5.7	125	245	7.0	6.0	136	244
B-N*	7.3	6.0	114	170	6.9	5.7	102	198	8.6	5.7	136	244	7.0	5.8	79	201
B-P*	7.4	6.0	102	170	6.8	5.7	102	198	8.9	5.7	102	228	7.3	6.0	79	191
B-NP*	7.8	6.0	91	189	7.0	5.9	79	139	9.1	5.5	114	196	7.2	6.5	69	172
B-C*	8.4	6.0	91	209	7.1	5.8	114	226	8.8	5.7	125	245	7.6	6.0	91	181
B-CNP*	8.5	5.9	114	226	7.4	7.0	45	125	9.2	6.6	79	151	8.2	6.2	57	153
B-NP	8.1	5.9	114	206	7.5	5.7	91	199	9.2	5.8	91	199	8.2	6.2	45	165
B-C	8.1	6.0	8.0	180	7.0	5.7	91	219	7.7	5.7	102	218	8.0	5.8	79	191
B-2CNP	8.1	6.0	112	208	7.1	5.7	114	176	8.6	5.7	102	198	8.2	6.1	68	152
C-Cont	7.4	5.9	91	209	7.3	5.6	114	186	7.6	5.9	125	245	7.7	5.9	91	189
C-NP*	6.4	5.9	91	206	7.4	5.7	95	205	7.0	5.7	79	191	7.4	6.0	79	201
C-C*	7.4	5.9	114	186	7.7	5.8	159	171	8.2	6.2	68	172	7.8	6.0	79	211
C-CNP*	8.2	5.9	79	201	7.8	5.6	114	196	8.2	5.9	114	186	7.8	6.0	102	188
C-NP	6.7	5.9	114	189	7.9	5.6	102	228	7.8	5.6	68	172	7.5	6.0	79	197
C-1C	7.1	5.9	79	241	7.8	5.7	114	246	8.0	5.6	91	189	7.8	6.0	114	186
C-2C	6.7	5.9	79	241	7.5	5.6	102	218	7.7	5.6	79	161	7.9	6.0	73	207
C-3C	7.1	6.0	91	187	8.0	5.7	125	215	7.7	5.7	114	266	7.9	5.9	85	195
C-1CNP	6.5	5.9	91	216	8.0	5.8	102	188	7.8	5.8	57	192	7.5	6.1	79	205
C-2CNP	8.1	5.8	124	238	8.2	5.7	102	208	8.4	5.8	68	140	8.0	6.2	79	197
C-3CNP	7.6	5.8	102	241	6.5	5.5	228	312	6.5	5.7	102	218	6.1	5.8	159	255
LAKE	8.4	5.9	86	227	8.1	5.8	100	204	8.4	5.8	108	227	7.7	6.0	97	213

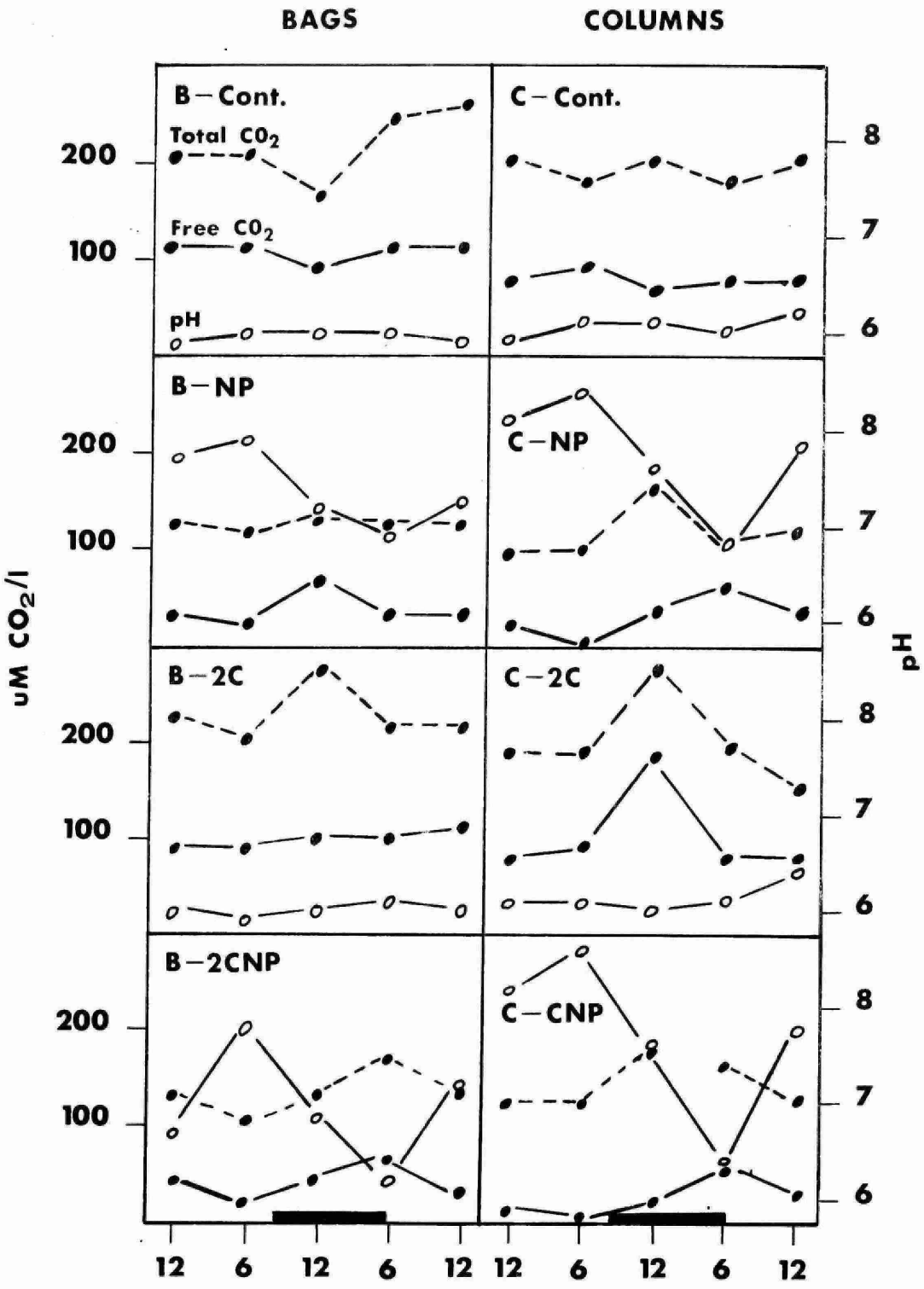

Figure 14

Diurnal variations in the pH, total and free carbon dioxide ($\mu M CO_2$/l) of eight enclosures (4 bags:4 columns) receiving daily feedings of glucose and/or nitrogen plus phosphorus toward the end of the field experiment.

Carbon, Nitrogen, Phosphorus

The carbon, nitrogen and phosphorus content of the total solids present in each tube over the period of the study was calculated from analyses of the weekly seston samples and the terminal periphyton. The relative percentage composition of the solids with respect to these three nutrients as well as weight to weight nutrient ratios are presented in Table X.

The carbon, nitrogen and phosphorus requirements of the total algae of each tube was estimated using the following relationships - $\mu gP/mm^3 = 1$, $\mu gN/mm^3 = 20$, $\mu gC/mm^3 = 100$. A comparison between the actual nutrient content of the solids in each tube and the calculated algal requirements (Figure 15) shows the solids to contain, at a minimum, at least three times the amount of carbon, nitrogen or phosphorus necessary to support the algal quantities which developed.

DISCUSSION

Comparison of the mean values of several parameters measured in 1967 and 1972 (Table XI) shows very little change to have occurred in Kushog Lake during the five year period with respect to water transparency or phytoplankton density. On the other hand, total phosphorus appears to have declined by 1972 to a level less than one-third of the 1967 value whereas nitrate nitrogen has increased somewhat. Whether this apparent decrease in total phosphorus is related more to improved analytical technique or to the disappearance of a boy's camp and improved sewage treatment at a boarding

TABLE X

Percentage of Total Solids as Carbon, Nitrogen, Phosphorus and C:N:P Ratios From the Enclosure Study

	C	N	P	C	N	P
B-Cont	31.6	3.7	0.16	196	23	1
B-N*	48.7	6.8	0.27	182	25	1
B-P*	25.6	3.1	0.23	110	13	1
B-NP*	43.1	8.6	0.52	82	16	1
B-C*	64.3	3.6	0.23	282	16	1
B-CNP*	32.6	5.5	0.34	95	16	1
B-NP	24.4	5.2	0.41	60	13	1
B-2C	34.1	5.3	0.21	161	25	1
B-2CNP	40.6	5.3	0.41	99	13	1
C-Cont	50.6	4.9	0.22	232	22	1
C-NP*	38.1	4.8	0.29	130	16	1
C-C*	17.3	3.5	0.24	71	14	1
C-CNP*	16.2	3.6	0.16	98	22	1
C-NP	23.3	3.8	0.25	92	15	1
C-1C	13.3	2.8	0.16	81	17	1
C-2C	15.6	3.8	0.22	71	17	1
C-3C	15.7	5.1	0.18	90	29	1
C-1CNP	36.3	5.6	0.54	66	10	1
C-2CNP	20.2	3.7	0.32	62	11	1
C-3CNP	10.5	3.4	0.15	68	22	1

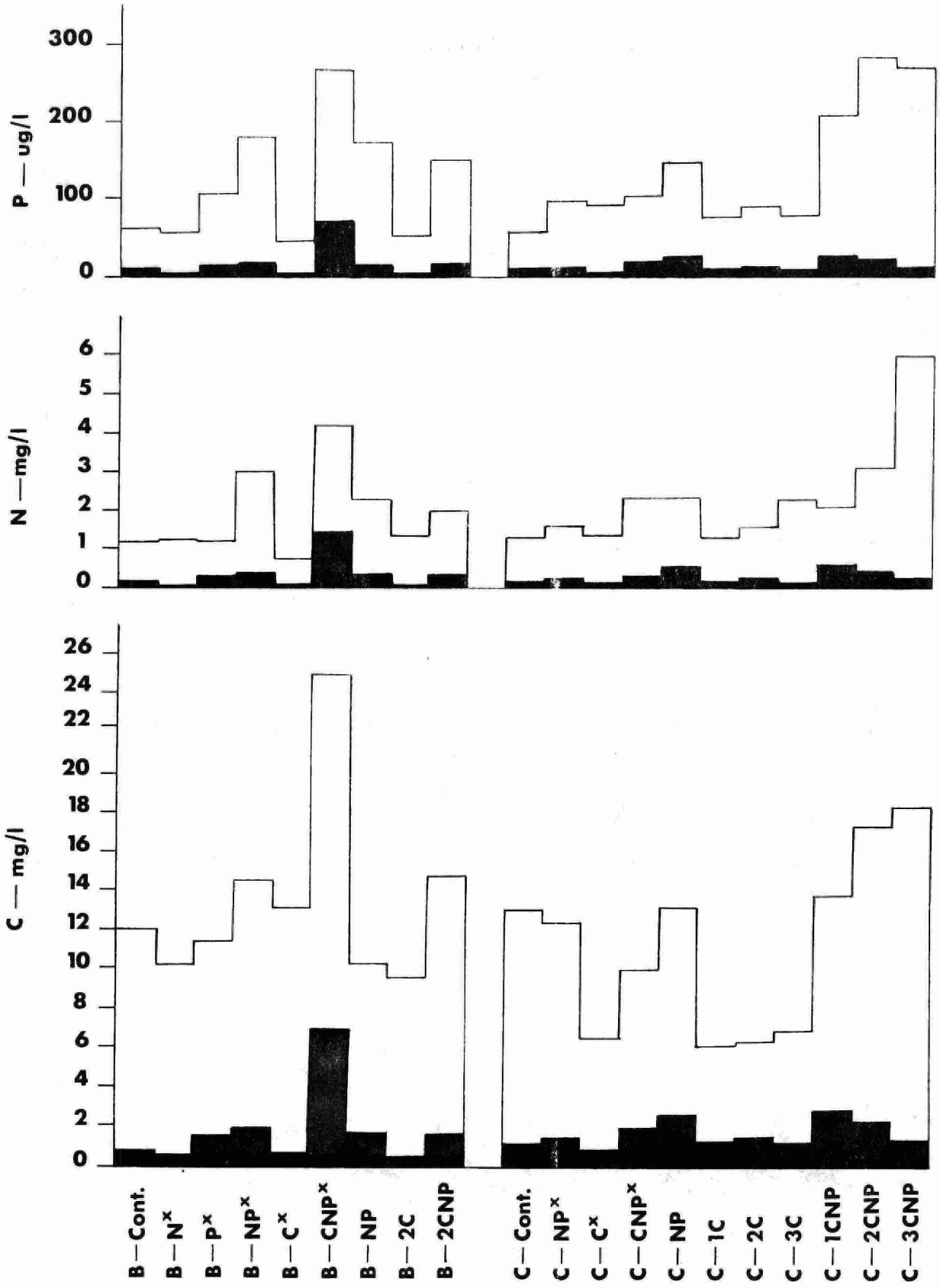

Figure 15

A comparison between carbon, nitrogen and phosphorus content of the total solids of each enclosure with the estimated requirements of the associated algal populations.

TABLE XI

A comparison of the mean values of parameters measured in 1967 and 1972

		1967	1972
Calcium	mg/l	5.0	5.0
Magnesium	mg/l	1.5	1.0
Potassium	mg/l	0.5	0.4
Sulphate	mg/l	10	9
Total Iron	mg/l	0.10	0.10
Nitrate:N	µg/l	74	90
Phosphorus	µg/l	33	10
Secchi Disc	metre	4.3	4.9
Algae	mm^3/l	0.63	0.44
Chlorophyll a	µg/l	1.4	1.0

school, both located on the lake draining into Kushog, is not possible to acertain.

Weight to volume relationships between the carbon, nitrogen, phosphorus and phytoplankton content of the seston ($\mu g/mm^3$) are illustrated in Figure 16. Techniques of Fitzgerald and Nelson (1966) to establish essential phosphorus requirements of algae when applied to seston samples from several Ontario surface waters (Christie, 1973b, 1973c) yielded various phosphorus and nitrogen to biomass ratios. The presence of these nutrients in excess of phytoplankton requirements was indicated when the observed ratios were in excess of $\mu g\ P/mm^3 = 1$, $\mu g\ N/mm^3 = 20$. Such ratios should not be interpreted as indicating all the phosphorus and nitrogen of the seston is necessarily available to the algae. On the other hand the appearance of ratios less than the above, as observed occasionally in the trophogenic waters of Kushog, would suggest that phytoplankton development is restricted as a result of a limited availability of one or both nutrients.

According to Mullin et al (1962) the carbon content of algae may vary from 30 - 250 $\mu g\ C/mm^3$. Ratios obtained in 1971, 1972 for the most part exceed this range at all depths until midsummer in the epilimnetic and metalimnetic zones. The appearance of carbon/algal ratios greater than 250 $\mu g\ C/mm^3$, in conjunction with similar excessive ratios obtained with phosphorus and nitrogen would suggest the presence of suspended materials which contain very little algae, such as organic detritus originating from adjacent forested shoreline either directly as pollen, or as part of the natural surface run-off.

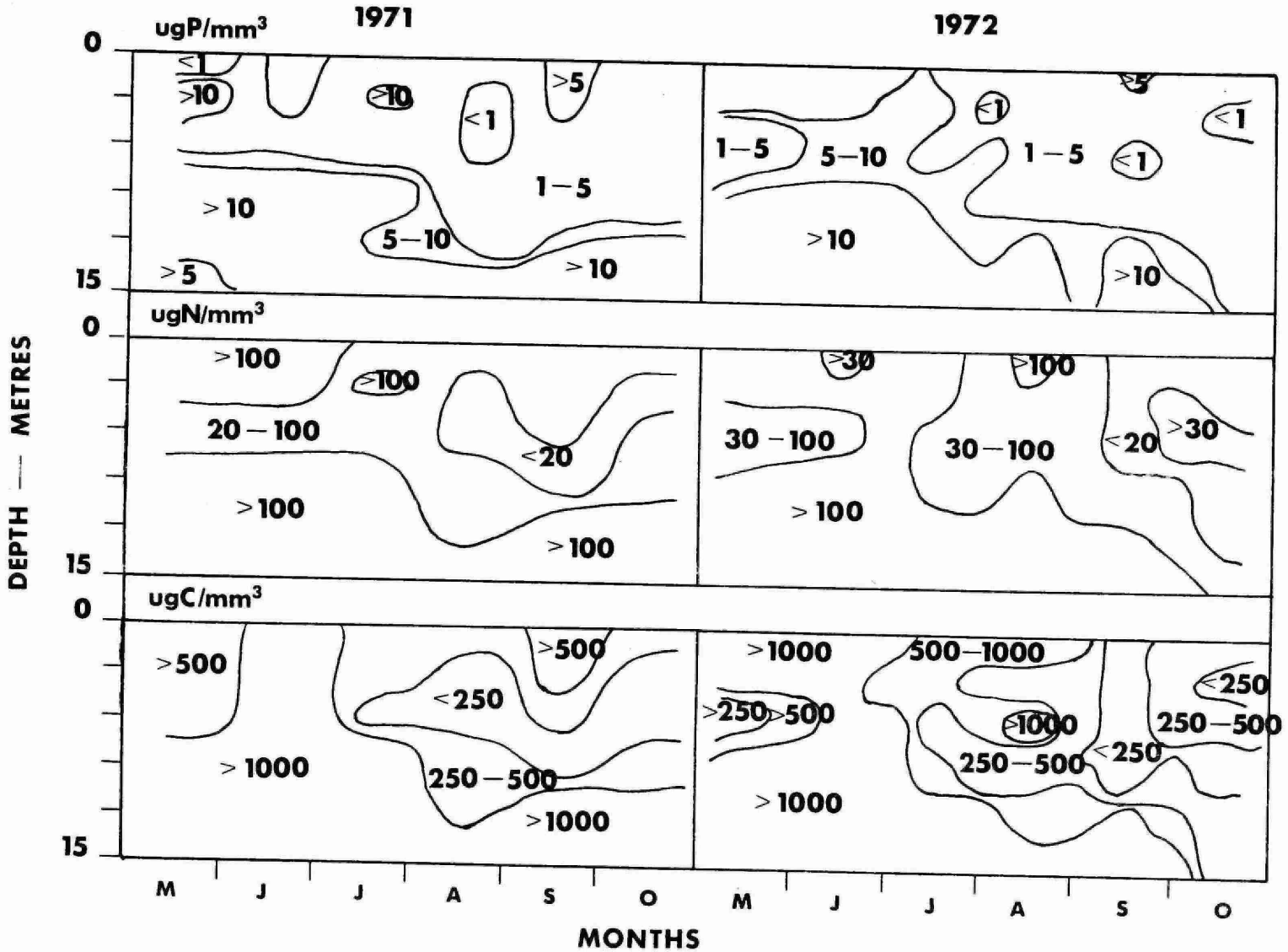

Figure 16

Ratios between the carbon, nitrogen and phosphorus content of the seston and associated phytoplankton populations. (nutrient (µg)/algal(mm^3)).

Midsummer profiles of carbon assimilation (Figure 9) and secchi disc estimates of water transparency (Figure 3) depict features very similar to those observed by Findenegg (1964) in Lunzer See which is considered an example of oligotrophy. Maximum standing crops of the trophogenic zone of Kushog each year did not exceed 2 mm^3/l which is less than the range of 3 - 5 mm^3/l suggested by Vollenweider (1970) for a mestrophic situation. Kushog Lake in 1971 and 1972, as in 1967, would therefore appear to represent an example of an oligotrophic environ.

A maximum algal response of 61 µg/l chlorophyll a, obtained during a laboratory enrichment experiment with a winter sample of lake water (Figure 10), would suggest that the epilimnetic waters of this lake are sufficiently endowed with various growth factors essential for plant growth, other than nitrogen and phosphorus, to support much larger quantities of phytoplankton than were observed during examination of the lake in 1971 or 1972. A synergistic increase to addition of nitrogen plus phosphorus, a result similarly observed by Christie (1969), Thomas (1969), Polsini et al (1970) and Glooschenko and Alvis (1973) Sakamota (1971) indicates a dual limitation on phytoplankton responses related to the supply of these two nutrients, and more particularly phosphorus. Addition of this nutrient alone developed a maximum response more than double the control.

The results of the in situ fertilization experiments show that only those enclosures receiving phosphorus developed either a maximum phytoplankton or total algal quantity more than double the control tubes (Figure 11, Table VI).

Slug feedings of nitrogen or carbon had very little if any stimulatory effect on algal responses. Addition of only nitrogen plus phosphorus (B-NP*) while evoking a synergistic reaction in photosynthetic activity displayed no apparent similar action on the basis of algal biomass. Synergistic responses in photosynthetic activity and algal development are evident when carbon was added along with nitrogen and phosphorus (B-CNP*)(Figure 11, Table VIII).

The quantities of suspended solids on the last day of the experiment (seston plus periphyton) of the column enclosures receiving daily increments of nitrogen and phosphorus are essentially equivalent (Figure 12). The algal and faunal populations of the lowest carbon treatment (C-1CNP) at that time were found to be about three times that of the column enclosure receiving equivalent nitrogen and phosphorus but no carbon (C-NP). With an increased daily loading of glucose the algal population declined (C-1CNP versus C-2CNP) suggesting a shift in the balance of nutrient competition for nitrogen and phosphorus away from the algae in favour of a non-chlorophyllous heterotrophic population: strands of fungal mycelium were very evident in tube C-3CNP during the latter part of the study.

Routine examination of inorganic carbon concentrations show the decrease in the level of this parameter to be greatest in those systems receiving daily increments of nitrogen plus phosphorus (Table IX). Diurnal observations toward the end of the investigation further indicate that carbon dioxide during the daytime is disappearing faster than net replenishment in those enclosures fertilized with nitrogen and phosphorus (Figure 15).

Such static determinations do not indicate the rate of availability of carbon dioxide for photosynthetic assimilation, or in other words these measurements are not indicative of the amount of carbon dioxide used because quantities available as a result of atmospheric infiltration and respiration could not be assessed in total. The degree to which the carbon dioxide pool is refurbished, in the absence of photosynthetic activity, as indicated by the quantity present just before sunrise, is not as great in those tubes receiving only nitrogen plus phosphorus as when glucose was also included. The biodegradation of glucose to carbon dioxide could then account for the establishment of a larger pre-dawn concentration plus a possible higher rate of carbon dioxide availability during daylight hours and thus result in an enhancement of autotrophic processes (B-CNP*) which might otherwise have been restricted due to a decreasing availability of carbon dioxide (B-NP*) even though nitrogen and phosphorus may not have been limiting to phytoplankton development. Heterotrophic growth of algae may also have been occurring, however the extent to which this type of phenomenon may have influenced the development of algae can not be assessed from these results.

Between bag and column enclosures of comparable nutrient regimes algal development of the columns is typically less than that of the bags. Total combined populations of rotifers and crustaceans illustrate the reverse situation, being greater in the columns (Figure 17). Such a disparity is not unexpected however as the innoculum of the bags does not include organisms either adjacent to or within the muds, having been more or less established at the time of filling.

The discrepency between the algal responses of comparable treatments in the two types of enclosures no doubt reflects to some extent the impact of this latter difference. For example while the total solids of B-CNP* and C-CNP* are quite similar (Table VI), the faunal population of the latter is approximately three times that of the former, whereas the algal populations show a reverse relationship. Predation by the microfauna could therefore conceivably account for the absence of a synergistic algal response to carbon plus nitrogen plus phosphorus in treatment C-CNP*.

Schindler et al (1973) have recently demonstrated that although daytime levels of free carbon dioxide may be become virtually undetectable in a shield lake fertilized with nitrogen and phosphorus, maximum algal densities in excess of 15 mm^3/l were recorded. The absence of equivalent densities in the tubes of this study could reflect the impact of faunal predation in both types of enclosures, populations of these organisms being several orders of magnitude higher than were observed, for example, in a fertile shield environ such as the Muskoka Lakes (Michalski et al, 1973).

Detailed comparison of the algal responses of the Kushog experiments with the observations of nutrient enrichment studies with enclosures in various other shield lakes (Schindler et al, 1971; Michalski et al, 1973) is not possible due to differences in the type of enclosure, background fertility history, fertilization rates etc. The results of all such experiments clearly indicate however that phytoplankton development in these waters is primarily related to the availability of phosphorus.

CONCLUSION

Kushog Lake represents an oligotrophic, low alkalinity environ which does not develop an anaerobic hypolimnion when thermally stratified during the summer months.

Phytoplankton development in the trophogenic zone in late summer would appear restricted due to a low availability of nitrogen and phosphorus, otherwise the lake water is quite fertile.

Phytoplankton responses associated with in situ isolated epilimnetic water in bag and column enclosures to single and daily feedings of glucose, nitrogen, phosphorus were quite variable. The key nutrient influencing phytoplankton development was found to be phosphorus availability. Addition of glucose or nitrogen alone had no stimulatory impact. A synergistic response to C + N + P compared to N + P appears related to an enhanced availability of carbon dioxide.

Differences between phytoplankton responses of bag versus column enclosures receiving equivalent treatments is attributed to the impact of faunal predation.

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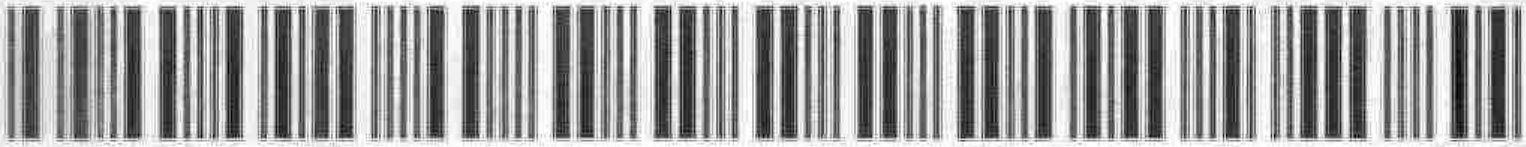
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